(54) **Position to Phase Transducers**

(57) A linear variable phase transformer or position to phase transducer (1) produces a linear phase change in an output signal with respect to displacement. Moreover, the magnitude of such output signal remains relatively constant while such displacement occurs. The transducer (1) includes two primaries (6, 7) which are specially wound according to sine and cosine functions and are excited out of phase, a secondary (8) and a core (14) that combines the primary signals and induces the output signal in the secondary according to the core position relative to the primaries.
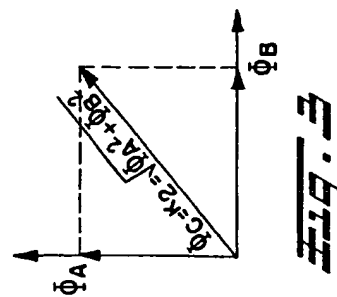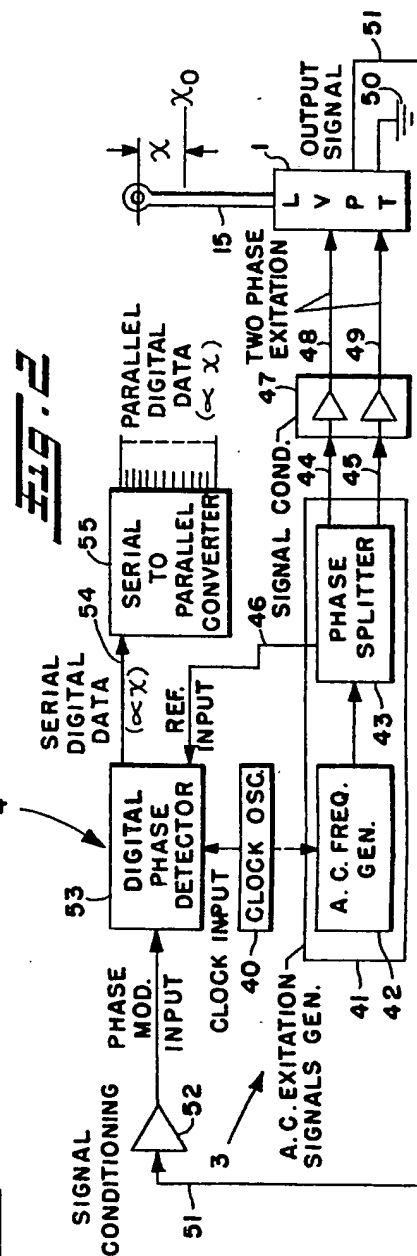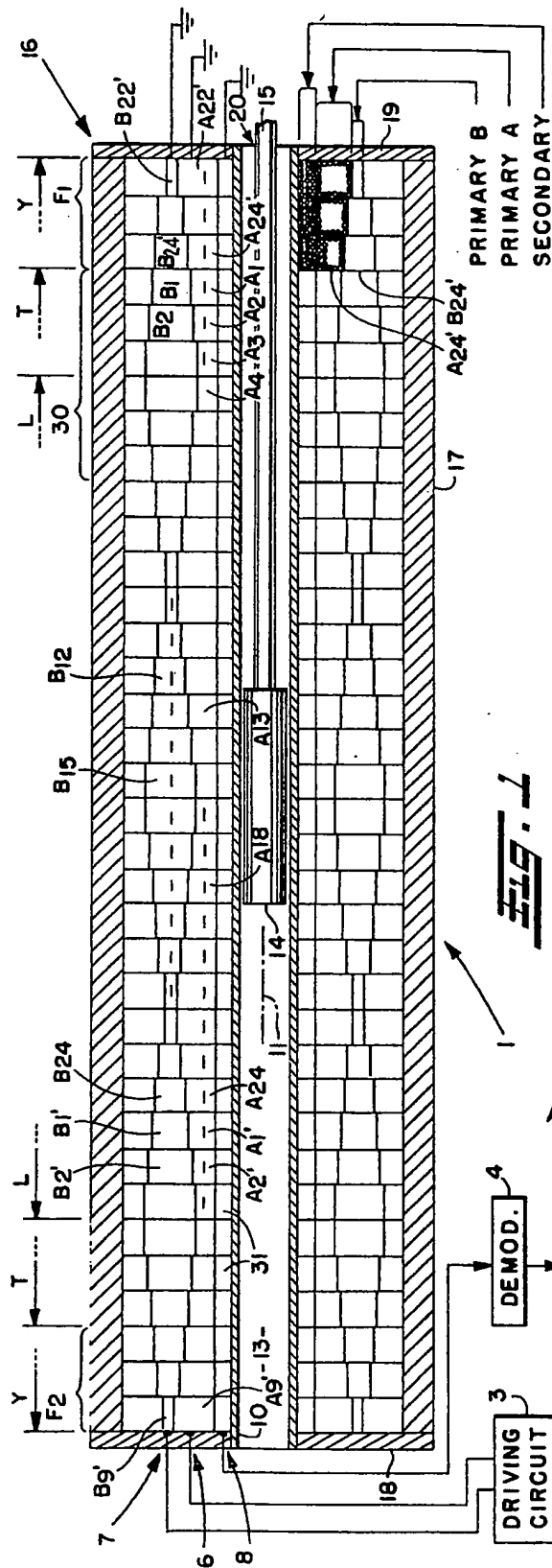
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FIG. 1

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Fig. 1

16, B22', A22', 20, 15, 19

PRIMARY B, PRIMARY A, SECONDARY

Y F1, T, L, 30

17, A24 B24', A24' B24

B2 B1 B14, B4

$A_4, A_3, A_2, A_1, A_{24}$

B12, A13, A18, B15, A18, 14

B24, A24

B2' B1' B24, L, T, Y F2

A2' A1' A24, 31, 10, A9, 13, B9'

7, 6, 8, 18

4 DEMOD.

5 UTILIZATION CIRCUITRY

3 DRIVING CIRCUIT

1, 2

Fig. 2

X_0, X, 15

OUTPUT SIGNAL, L V D T, 50, 51

TWO PHASE EXITATION, 47

48, 49, 44, 45

PHASE SPLITTER, 43

A.C. FREQ. GEN., 41, 42

A.C. EXITATION SIGNALS GEN., 3

SIGNAL COND., 46

REF. INPUT

SERIAL TO PARALLEL CONVERTER, 55

PARALLEL DIGITAL DATA ($\propto X$)

54, SERIAL DIGITAL DATA ($\propto X$)

DIGITAL PHASE DETECTOR, 53

CLOCK INPUT, CLOCK OSC., 40

PHASE MOD. INPUT

SIGNAL CONDITIONING, 52, 51

4

Fig. 3

Φ_B

$\Phi_C = \frac{1}{2}(\Phi_A + \Phi_B)$

$\frac{\Phi_A}{2}$, $\frac{\Phi_B}{2}$

Φ_A

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SPECIFICATION
Displacement to Phase Transducers

The present invention relates to displacement to phase transducers.

The disclosures of our following patent publications (hereinafter referred to as 'the initially-
5 mentioned patent publications') are hereby incorporated herein by reference: 5
US Patent No. 4,134,065—'Linear Variable Phase Transformer';
US Patent No. 4,138,632—'Pulse Width Modulator Digital Servo System'; and
Published UK Patent Application GB 2 007 367A—'360 Degree Linear Variable Phase
Transformer'.

10   Prior linear variable phase transformers (LVPT's) disclosed in the initially-mentioned patent   10
publications convert position information to a phase quantity or time-based relationship, which may
be readily demodulated to provide a system output signal, for example, in a digital format. Plural
linearly disposed non-overlapping primary windings of such LVPT's are energised or excited by
respective AC excitation signals of the same frequency but ordinarily phase separated by other than 0°
15 or 180° to produce in a relatively movable core axially oriented magnetic fluxes similarly out of phase.   15
The fluxes are vectorially summed or combined in the core and the combined flux vector or output flux,
which has a phase related to the positional relationship of the core and primaries, induces in a
secondary an electrical output signal which has a corresponding phase. Accordingly, the phase of the
output signal is directly related to the phase of the flux in the core, and it is the relative mix of primary
20 excitations in the core that phase modulates an output signal to indicate the core position.   20
However, the magnitude of the output voltage was not controlled and in fact varied up to about
30% over the measurable stroke length. In some circumstances, though, it is desirable to hold such
output voltage relatively constant, for example, to simplify the output circuit so it does not have to be
insensitive to level. Then, an output signal reduction may be readily used for fault detection.
25   In the initially-mentioned patent publications, circuitry is disclosed for energising or exciting the   25
respective LVPT primaries by phase separated and generally constant current AC excitation signals. A
demodulator circuit, such as a zero crossing detector, detects the phase difference between the phase
modulated output signal and a reference signal and whether the output signal leads or lags the
reference signal, thereby to provide system output information indicative of the position of the core
30 relative to the primaries, for example, with respect to a known null position. The system output   30
information may be displayed or used for other control or like purposes.
To linerise the change in phase of the output signal with respect to core position (hereinafter
referred to as linearity) the primaries of the prior LVPT's are wound in accordance with the solution of a
particular arc tangent function and/or many primaries with respective excitations are used. Also, in GB
35 2 007 367A there are disclosed antifringing primaries which reduce fringing effects as the core moves   35
to extremities of the transducer, thereby further increasing the linearity thereof.
One type of transducer that produces an output signal which varies in amplitude with respect to
position is a linear variable differential transformer (LVDT). Although the input and output signals of
LVDT's are sometimes described as phase related, the term 'phase' there means polarity of an
40 alternating current wave form. Other positions transducers include moving coils wound on   40
magnetically permeable material, such as resolver and synchro devices, or printed coils on
magnetically permeable materials such as Inductosyne devices, but these require moving contacts or
wires. A Selsyn device disclosed in U.S. Patent 2 988 697 indicates the position of a movable core by
combining radial flux vectors such that the geometric orientation of the flux vectors provides output
45 information. In another position transducer disclosed in US Patent 2,911,632 the amplitude of the   45
voltage induced in a secondary winding provides an indication of the position of a movable core.
According to a first aspect of the invention there is provided a displacement to phase transducer,
comprising plural primary means for producing in response to alternating current excitation alternating
magnetic fluxes, combining means for producing an output flux having a phase dependent on the
50 relative positions of said combining means and said primary means, at least one said combining means   50
and primary means being movable relative to the other, and output means for producing an output AC
electrical signal having a substantially constant magnitude and a phase corresponding to the phase of
said output flux.
According to a second aspect of the invention there is provided a displacement to phase
55 transducer, comprising plural segmental and generally coaxial primary means for producing in response 55
to alternating current excitation alternating magnetic fluxes, combining means for producing an output
flux having a phase dependent on the relative positions of said combining means and said primary
means, at least one of said combining means and primary means being movable relative to the other,
and output means for producing an output AC electrical signal having a phase corresponding to the
60 phase of said output flux.   60
According to a third aspect of the invention there is provided a displacement to phase transducer,
comprising plural primary means for producing in response to alternating current excitation signals
having a phase separation respective alternating magnetic fluxes, combining means for producing an
output flux having a phase dependent on the relative positions of said combining means and said

primary means, at least one of said combining means and primary means being movable relative to the other, the maximum variation of said phase of said output flux with respect to the maximum displacement of said combining means and primary means being larger than said phase separation of said excitation signals, and output means for producing an output AC electrical signal having a phase
5   corresponding to the phase of said output flux.   5
         In this specification, 'primary winding' and 'secondary winding' are also referred to as 'primary' and 'secondary', respectively. 'Position' may be used to specify the positional relationship of the combining means (e.g. an LVPT core) and the primaries or to denote relative displacement of the combining means, for example, from a null position, 'displacement', accordingly, indicating the amount
10   of position change. 'Phase' means the actual phase of an AC electrical signal or magnetic flux signal, or   10
     the separation relationship thereof to the phase of a reference such signal, as opposed to a polarity relationship. 'Phase quantity' means the phase difference between the phase modulated output signal of a transducer embodying the invention or a square wave logic signal wave form in phase therewith, for example, and a reference signal; such phase quantity ordinarily will be distinguished with a polarity
15   of its own to indicate whether the phase of the output signal is leading or lagging the reference signal.   15
     'Excitation phase' or 'excitation signal' means an AC electrical signal of a particular phase for exciting a primary and may be used interchangeably. 'Digital form' or 'digital format' means any form of digital-type number of electronic representation thereof, as opposed to an analog representation thereof.
         In an LVPT constituting a preferred embodiment of the invention and described in more detail
20   hereinbelow, the output level, i.e. the magnitude of the voltage, for example, of the output signal, is   20
     maintained substantially constant while the phase of the output signal is modulated substantially linearly with respect to position. Plural (preferably two) primaries of the LVPT produce in response to respective alternating current excitations alternating magnetic fluxes that are combined in a core. The combined flux in the core induces an output AC electrical signal in a secondary with such signal having
25   a substantially constant magnitude and a phase corresponding to that of the combined or output flux.   25
     Moreover, the plural, say two, primaries, which are energised by respective excitation signals, are so wound that the maximum variation of the output flux phase with respect to maximum displacement, say of the core relative to the primaries, may exceed the phase separation of the excitation signals. For example, as will be described further below, two excitation signals that are phase separated by 90°
30   excite two respective primaries; yet the output signal phase actually is variable over a full 360° period.   30
         The LVPT embodying the invention will be described below as including only two primaries that are respectively excited by excitation signals which are in quadrature, this combination providing the least complex, embodiment of the invention. However, in view of the following disclosure, it will be understood that those skilled in the art that other embodiments of the invention may use more than
35   two primaries or excitation signals that are phase separated by other than 90°.   35
         Thus, the LVPT constituting the preferred embodiment includes two segmental and generally coaxial primaries, each primary segment being positioned along the LVPT axis for selective coupling with the core, depending upon the relative positions thereof, and each segment including a plurality of circumferential turns around the axis. The number of turns in each primary segment and the direction
40   they are wound are determined in accordance with mathematical constraints, thereby to provide the   40
     substantially constant magnitude output signal and relatively large phase variation thereof in response to respective AC excitation signals and relative core position. In the preferred form the number of turns in the respective segments varies according to a sinusoidal function.
         The LVPT requires only two primaries and, therefore, only two excitation signals, thus
45   necessitating relatively simplified circuitry for energising the same. However, since each primary may   45
     have many primary segments, thereby increasing the number of times the error function of the system theoretically passes through zero, there will be a high degree of linearity between the output signal phase and the core displacement.
         Since the output information provided by the LVPT is an accurate time-based signal, such
50   information can be used directly in analog form or readily demodulated, as in the above applications,   50
     to convenient digital format. Moreover, the LVPT has the various features and advantages of the prior LVPT's, including, for example, relatively large maximum core stroke to total LVPT length ratio, linearity accuracy, and efficiency of size, weight, strength, isolation, operative temperature range, etc.
         The LVPT constituting the preferred embodiment of the invention includes the following
55   advantageous features. One can obtain maximum phase variation of an output signal with respect to   55
     displacement, i.e. a change in position, using a minimum number of LVPT primaries, and, more particularly, obtain a full 360° or more phase variation although the phase separation of the excitation signals is less than 360°. The output signal phase variation is capable of exceeding the total phase separation of the excitation signals delivered to the position to phase transducer. The output signal
60   has a substantially constant magnitude. The accuracy of the transducer is improved. The circuitry   60
     requirements for energising the position to phase transducer are minimised, while maintaining a relatively high degree of accuracy of the output signal thereof.
         The invention will now be further described, by way of illustrative and non-limiting example, with reference to the accompanying drawing, in which:
65   Figure 1 is a schematic cross sectional view of a sine cosine LVPT in accordance with the present   65

invention:

Figure 2 is a schematic circuit diagram illustrating drive and demodulator circuitry for use in an
system with the LVPT of Figure 1; and

Figure 3 is a vector diagram representing quadrature related signals occurring in the LVPT.

Referring now in detail to the drawing, a since cosine linear variable phase transformer (LVPT) is
generally indicated at 1 in Figure 1 as part of an LVPT system 2 that also includes a drive circuit 3, a
demodulator circuit 4, and utilisation circuitry 5. The LVPT 1 has two primaries 6, 7 and a secondary 8,
each of which is formed by a plurality of generally circumferential turns of respective conductors about
a nonmagnetic bobbin 10. The bobbin 10 is located along the axis 11 of the LVPT 1, such axis being
linear in the illustrated embodiment, it being understood, though, that the axis also may be nonlinear,
such as circular, if desired. Within a hollow interior 13 of the bobbin a core 14 is positioned for
movement relative to the primaries and secondary along the axis 11. A rod 15 coupled to the core
extends beyond the LVPT case 16, which includes a cylindrical cover 17 and end plates 18, 19,
through an opening 20 in the latter for mechanical connection to an external device, the position of
which is to be detected by the LVPT 1. The bobbin 10 and case 16 may provide physical, e.g.
temperature, pressure, humidity, etc., isolation of the respective electromagnetic coils forming the
primaries and secondary.

In operation of the LVPT 1, the primaries 6, 7 are excited by the drive circuit 3 with excitation
signals that are in quadrature. The excited primaries produce in the core 14 respective independent
magnetic fluxes Φ_A (due to the A primary 6) and Φ_B (due to the B primary 7). Those independent fluxes
are combined in the core 14, and the combined or output flux Φ_C in the core causes an AC output
signal to be induced in the secondary 8.

The phase of the output signal in the secondary 8 will depend on the phase of the combined flux
in the core 14 and will vary according to the relative displacement x of the core 14 relative to the
primaries 6, 7. In the following description it will be assumed that the core 14 is attached by the rod 15
to an external device, not shown, for movement therewith while the remaining parts of the LVPT 1,
including the coils forming the primaries and secondary, ara relatively fixed in their location; however, it
will appreciated that the core may be maintained fixed and the coils moved so long as relative
displacement is effected between the core and the coils. The output signal phase provides an analog
indication of the core displacement, and this phase information can be demodulated in the
demodulator circuit 4 to provide digital or other output information that can be readily used in the
utilisation circuitry 5, e.g. for display, feed-back control, or like purposes.

In the present LVPT 1, it is intended that the phase angle ϕ_c of the flux in the core 14 varies
linearly with respect to displacement x. Therefore, the derivative of that phase angle ϕ_c with respect to
displacement x, i.e. the change in such phase angle with respect to displacement, should be
maintained constant. Moreover, in the present LVPT 1 it is intended that the magnitude of the output
flux Φ_C in the core 14 and, thus, of the AC output signal induced in the secondary 8, be maintained
constant. The following analysis describes the discovery for effecting such constraints to produce the
LVPT 1.

The graph of Fig. 3 illustrates the quadrature relationships of the fluxes Φ_A and Φ_B as vectors
induced in the core 14 by the respective excited primaries 6, 7. Also illustrated is the combined output
flux Φ_C vector, formed by taking the square root of the sum of the squares of fluxes Φ_A and Φ_B, as is
well known due to their quadrature relationship. The constraints of the LVPT 1, then, are such that the
magnitude of the output flux Φ_C vector remain substantially constant and that the phase angle thereof
vary substantially linearly with respect to relative core displacement.

The output flux Φ_C induced in the core 14 equals the vector sum of the fluxes Φ_A and Φ_B
independently induced by the A and B primaries 6, 7 with each independent flux being directly
proportional to the current through the respective primary and the number of turns of that primary
effectively cut by or electromagnetically coupled to or seen by the core 14. Assuming that each of the
primaries 6, 7 is energized by respective AC excitation signals I_A and I_B of equal maximum amplitudes I
and of phase separation θ, where θ equals 90° here for the excitation signals to be in quadrature, the
currents through the respective primaries as a function of time can be written, as is well known, as
follows:

1) $$I_A = I \sin(wt + \frac{\theta}{2})$$

2) $$I_B = I \sin(wt - \frac{\theta}{2})$$

These equations can be reduced, as follows, assuming the mentioned quadrature relationship:

3) $I_A = I \sin wt = I\ 0°$

4) $I_B = I \cos wt = I\ 90°$

The latter part of equations 3 and 4 relates the two currents and their relative phase angles.

In the frequency domain mathematically the phase angle ϕ_c of the flux in the core 14 is, as follows:

5)
$$\phi_c = \arctan \frac{\Phi_A}{\Phi_B} \cdot \tan \frac{\theta}{2}$$

where Φ_A and Φ_B, respectively, are the independent fluxes induced in the core 14 and coupled to the secondary 8 for a given position x of the core due to the primaries 6, 7 and θ is the phase separation of the two fluxes or of the excitation signals. In the present case the excitation signals are in quadrature so the phase separation is 90° and the tangent term of equation 5 becomes unity.

The derivative of equation 5 with respect to displacement x is equated to a constant K_1, as follows:

6)
$$\frac{d\phi_c}{dx} = \frac{d}{dx} \arctan \frac{\Phi_A}{\Phi_B} = K_1$$

which defines the desired linearity constraint to assure a linear relationship between the phase ϕ_c and displacement x.

The fluxes Φ_A and Φ_B relate to the ampere-turns of the respective primaries coupled to the core, as defined in the following equations:

7)
$$\Phi_A = CI_A n_a,$$

8)
$$\Phi_B = CI_B n_b.$$

where C is a proportionality constant, I_A in the absolute value of current I through primary 6 at a phase angle of 0° and I_B similarly is the current I through the primary 7 at a relative phase angle 90°, and n_A and n_B are the respective number of turns of primaries 6, 7 coupled with the core 14 at position x relative to the primaries.

Substituting the equalities of equations 7 and 8 into the frequency domain, equation 5 for flux angle ϕ_c, the following relationships can be derived.

9a)
$$\phi_c = \arctan \frac{CI_A n_A}{CI_B n_B}$$

9b)
$$\phi_c = \arctan \frac{I\,0°\,n_A}{I\,90°\,n_B}$$

9c)
$$\phi_c = \arctan \frac{n_A I}{n_B I} \tan 45°$$

the latter tangent function, of course, compensating for the phase angle separation of the two excitation currents and cancelling out to unity in view of the quadrature relationship of the excitation currents. Thus, the phase angle ϕ_c can be expressed as an arc tangent function as the "coupled" turns n_A, n_B, as follows:

9d)
$$\phi_c = \arctan \frac{n_A}{n_B}$$

The above linearity constraint of equation 6 now can be equivalently restated, as follows:

10)
$$\frac{d}{dx} \arctan \frac{n_A}{n_B} = K_1.$$

Since the independent fluxes induced in the core are in quadrature, they are combinable according to the Pythagorean theorem, whereby in the frequency domain the square of the absolute magnitude of the flux Φ_A plus the square of the absolute magnitude of the flux Φ_B equals the square of the flux Φ_C in the core, as shown in Fig. 3. To maintain the flux in the core Φ_C constant, say equal to a value K_2, the sum of the squares of the fluxes Φ_A and Φ_B also must be kept constant as follows:

11)
$$\Phi_A{}^2 + \Phi_B{}^2 = K_2{}^2 = \Phi_C{}^2$$

Assuming continued analysis in the frequency domain and equal and constant magnitudes I of

the currents I_A and I_B, equation 11 can be rewritten in accordance with the equalities presented in equations 7 and 8, as follows:

12) $C^2I^2n_A^2+C^2I^2n_B^2=K_2^2$.

By transposing the constant terms of equation 12 that do not depend on displacement x, the following constant magnitude constraint relationship for the LVPT 1 can be established:

13) $n_A^2+n_B^2=\dfrac{K_2^2}{C^2I^2}=K_3^2$,

wherein K_3 is a constant as long as the current amplitude I is maintained constant.

It has been discovered that one set of solutions that will satisfy both of equations 10 and 13 by relating the variables n_A and n_B to displacement x is, as follows:

14) $n_A=N \sin \phi (x)$

15) $n_B=N \cos \phi (x)$,

where N is an arbitrary number of ϕ (x) is the expected phase angle of flux induced in the core by the respective primaries, individually, as a function of the core position x with respect to the primaries. This solution requires that the windings of primaries 6, 7 overlap along preferably the total length Y of LVPT 1, a condition that was avoided in the prior LVPT's disclosed in the initially-mentioned patent publications for winding simplicity.

A practical application of the sine–cosine distribution of primaries defined in equations 14 and 15 is to quantize the distribution of winding turns along the total length Y of LVPT 1. That total length Y, which is the length of the bobbin 10 over which the primaries 6, 7 and secondary 8 are distributed, equals the stroke length L over which the core 14 is movable, plus the core length C, plus the axial length of portions F_1 and F_2, described further below, of the primaries 6, 7 that are used as anti-fringing primaries in the manner described, for example, in GB 2 007 367A. The antifringing primaries compensate for fringing effect at the extremities of the LVPT 1 to avoid nonlinearities due to a loss of magnetic signal at such extremities. Therefore, the core 14 ordinarily is precluded from moving into direct effective alignment with the anti-fringing primary portions F_1 and F_2 so that the total effective length T of the LVPT 1 over which the core moves equals the stroke length L plus the core length C.

To quantize the distribution of winding turns along the length of the LVPT, for a stroke length L of LVPT can be divided into M equal sections. Then, if the phase is to change 360°, for example, although any other phase change can be selected, with a displacement change of L, then for a displacement change of

$$\dfrac{L}{M}$$

the phase of the output signal must change 360° divided by M. Moreover, the core length C may be chosen at any practical length. For example, the core length should be sufficiently long to assure an effective length that is greater than the axial length of any one primary section or longer for the combining of more fluxes in the core, and the core should be sufficiently short so that a relatively efficient core length to stroke length is obtained.

One exemplary model, the present best mode, of LVPT 1 illustrated in Fig. 1 that complies with the foregoing constraints and assumptions will now be described. However, it will be appreciated that this description is exemplary only and that other distributions of winding turns may be utilized in an LVPT in accordance with the present invention.

For the exemplary model, the total phase change of the output signal is chosen 360° for a total stroke length L change. The number of sections M into which each primary is divided for achieving that total phase change is selected at 24. Accordingly, for each incremental position of the core

$$\dfrac{L}{M},$$

the phase change is about 15°. The core length is selected at one fourth the stroke length,

$$\dfrac{L}{4}.$$

To apply such quantizing technique for determining the number of winding turns in each of the twenty-four sections or segments designated A_1 through A_{24} of the A primary 6, starting at the right

hand end of the total effective length T of the primary 6 the distribution or number of turns at each section of coil 6 can be expressed by the following series:

$$N_{A_1}, N_{A_2}, N_{A_3}, N_{A_4}, \ldots N_{A_{M-1}}, N_{A_M}$$

5   This series is serially repeated for the sections A1' through A6', which compensate for or accommodate the core length C, and sections A7' through A9' and A22' through A24', which are the anti-fringing primary portions F_2 and F_1, respectively.

It is, of course known that the sine function (equation 14) is symmetrical about its maximum and about its zero crossing point, with a sign change occurring at the latter. Accordingly, it can be assumed that the sinusoidal distribution of windings formed by the various sections of primary 6 will have a
10   symmetrical and repetitious distribution, for example, being symmetrical about the sections having the maximum number of winding turns in each and being symmetrical with a sign change about the sections having a minimum number of winding turns in each. Assuming such symmetry and also assuming that the net effect of the first six sections A_1 through A_6 of primary 6 on the output signal when the core 14 is aligned therewith produces a zero output signal, whereby sine 0° equals zero, the
15   symmetry of the number of winding turns in the first six sections A_1 through A_6 of primary 6, as illustrated in Fig. 1, can be described by the following identities in which the subscripts A have been dropped for convenience: $N_6 = -N_1$; $N_5 = -N_2$; and $N_4 = -N_3$.

Similarly, symmetry about sections A_9 and A_{10}, a maximum number of turns N_9 and N_{10} and no sign or polarity change at those sections can be assumed since they are one fourth the stroke length L
20   from the sections A_3 and A_4. Also the net effect of sections A_7 through A_{12} on the output signal when the core 14 is aligned therewith provides a maximum output signal with sine 90° being a maximum, one. Therefore, the relationship of the numbers of turns in sections A_7 through A_{12} can be described, as follows:

$$N_7 = N_{12}; \ N_8 = N_{11}; \text{ and } N_9 = N_{10}.$$

25   Further, it is recognized that displacement along the LVPT 1 a distance

$$\frac{L}{2},$$

one half the stroke length, from the first-mentioned sections A_1 through A_6 to the sections A_{13} through A_{18} should find symmetry about sections A_{15} and A_{16} and the same number of turns, but with reverse phase, sign or polarity, per section corresponding, respectively, with the first-mentioned
30   sections. Thus, following relationship is realized:

17) $$\begin{aligned} N_{13} &= -N_1 = N_6 = -N_{18} \\ N_{14} &= -N_2 = N_5 = -N_{17} \\ N_{15} &= -N_3 = N_4 = -N_{16} \end{aligned}$$

Similar equalities relating the number of turns in sections A_{19} through A_{24} to the other sections
35   also can be defined, as follows:

18) $$\begin{aligned} N_7 &= N_{12} = -N_{19} = -N_{24} \\ N_8 &= N_{11} = -N_{20} = -N_{23} \\ N_9 &= N_{10} = -N_{21} = -N_{22} \end{aligned}$$

Thus, it will be seen that the entire winding pattern n_A of equation 14 above for the sections of
40   primary 6 will utilize only six different winding counts and respective opposite polarity connections for some of those to obtain the desired phase, polarity or sign. For example, the number of winding turns in primary section A_4 equals the number N_4, whereas the number of winding turns in the primary section A_3 equals N_3 turns. The numbers N_4 and N_3 are equal, and the minus sign designation in the matrix 17 indicates that the polarity of the electric connections to section A_3 is opposite from that of the
45   connections to the section A_4, etc.

Moreover, assuming that the output signal induced in the secondary by the first group 30 of sections A_1 through A_6 of primary 6 when the core 14 is effectively aligned therewith is zero and that as the core 14 travels incrementally by primary section to the left in Fig. 1, for example to alignment with primary sections A_2 through A_7, then with sections A_3 through A_8, etc., the phase of the output
50   signal due to the energized primary 6 changes by increments of 15°, etc., the equation 14 can be rewritten in conventional manner as six separate equations in six unknowns. For example, the second of such equations would be $N_2 + N_3 + \ldots + N_7 = N \sin 15°$. These equations also can be solved in conventional manner in conjunction with the equality matrices 17, 18 above to determine the number of winding turns in the respective sections of the primary 6. Although the solutions to such equations
55   may include fractional numbers, these may be rounded off in usual fashion.

Thus, choosing the number N of equation 14 to be 667, such simultaneous equations can be solved and rounded off to yield:

$$N_4 = 16 \text{ turns}$$
$$N_5 = 47 \text{ turns}$$
$$N_6 = 75 \text{ turns}$$
$$N_7 = 98 \text{ turns}$$
$$N_8 = 114 \text{ turns}$$
$$N_9 = 122 \text{ turns}$$

From these values, the matrices 17, 18 can be completed to indicate the desired number of turns in each section A_1 through A_{24} of the A primary 6. The primed sections A_1' through A_9' and A_{22}' through A_{24}' have the same number of turns and electrical connections of the corresponding unprimed sections, and it will be appreciated that such array or pattern of sections could, if desired, continue repeating depending on the length of the LVPT 1 and the character of the desired output signal.

The winding distribution in the sections B_1 through B_{24} and in the corresponding repetitive primed sections of the B primary 7 effectively are shifted or displaced 90°, that is the displacement

$$\frac{L}{4},$$

from the distribution provided in the A primary 6 inasmuch as they follow the cosine function of equation 15. Thus, the number of turns and the polarity of their connections in the sections B_1 and B_2 of the B primary 7 will be the same as those of the primary sections A_7 and A_8, respectively, *etc.* Therefore, the winding distribution for the B primary 7 will be identical with that of the A primary 6 except that the quantized sections of those primaries will respectively be shifted by an amount equal to 90°, *i.e.* one-fourth the total phase variation desired to occur over the stroke length of the LVPT 1.

In the exemplary model of LVPT 1 described above, each of the secondary sections 31 has 50 generally uniformly distributed winding turns. Chart 1 presents the number of turns and the polarity of the electrical connections thereof for each of the sections of the A primary 6 and B primary 7 of Fig. 1. Preferably the respective sections of the primary 6 are connected in series with the negative signs at certain sections indicating a current flow in a relatively opposite direction from that flowing in the other sections. The sections of the primary 7 also are similarly connected in series with each other, and the primaries are excited in quadrature by the driving circuit 3.

Chart 1

Note: Turns per Section ("—" indicates reverse direction); each secondary section includes 50 turns.

Primary A			Primary B		
A_{22}'	N_{22}	−122	B_{22}'	N_4	16
A_{23}'	N_{23}	−114	B_{23}'	N_5	47
A_{24}'	N_{24}	−98	B_{24}'	N_6	75
A_1	N_1	−75	B_1	N_7	98
A_2	N_2	−47	B_2	N_8	114
A_3	N_3	−16	B_3	N_9	122
A_4	N_4	16	B_4	N_{10}	122
A_5	N_5	47	B_5	N_{11}	114
A_6	N_6	75	B_6	N_{12}	98
A_7	N_7	98	B_7	N_{13}	75
A_8	N_8	114	B_8	N_{14}	47
A_9	N_9	122	B_9	N_{15}	16
A_{10}	N_{10}	122	B_{10}	N_{16}	−16
A_{11}	N_{11}	114	B_{11}	N_{17}	−47
A_{12}	N_{12}	98	B_{12}	N_{18}	−75
A_{13}	N_{13}	75	B_{13}	N_{19}	−98
A_{14}	N_{14}	47	B_{14}	N_{20}	−114
A_{15}	N_{15}	16	B_{15}	N_{21}	−122
A_{16}	N_{16}	−16	B_{16}	N_{22}	−122
A_{17}	N_{17}	−47	B_{17}	N_{23}	−114
A_{18}	N_{18}	−75	B_{18}	N_{24}	−98
A_{19}	N_{19}	−98	B_{19}	N_1	−75
A_{20}	N_{20}	−114	B_{20}	N_2	−47
A_{21}	N_{21}	−122	B_{21}	N_3	−16
A_{22}	N_{22}	−122	B_{22}	N_4	16

	Primary A				Primary B	
A_{23}	N_{23}	−114		B_{23}	N_5	47
A_{24}	N_{24}	−98		B_{24}	N_6	75
A_1'	N_1	−75		B_1'	N_7	98
A_2'	N_2	−47		B_2'	N_8	114
A_3'	N_3	−16		B_3'	N_9	122
A_4'	N_4	16		B_4'	N_{10}	122
A_5'	N_5	47		B_5'	N_{11}	114
A_6'	N_6	75		B_6'	N_{12}	98
A_7'	N_7	98		B_7'	N_{13}	75
A_8'	N_8	114		B_8'	N_{14}	47
A_9'	N_9	122		B_9'	N_{15}	16

Turning briefly to Fig. 2, a clock oscillator 40 provides a clock pulse input to an AC excitation signals generator 41. The generator 41 includes an AC frequency generator 42, which produces a square wave signal having a frequency depending on that of the clock pulse signal, and a phase splitter 43, which splits the square wave signal into two AC excitation signals on lines 44, 45, with such signals being in quadrature, i.e. out of phase by 90°. The phase splitter 43 also delivers a reference signal on line 46 to the demodulator 4, the reference signal having the same frequency as the signals on lines 44 and 45. A signal conditioner 47 converts the signals on lines 44 and 45 to conventional sinusoidal waves which are delivered via lines 48, 49 as the respective AC excitation signals to the primaries 6, 7 of the LVPT 1. The phase splitter 43 may include, for example, digital phase splitting circuitry, such as a plurality of flip-flops or the like. A grounding connection 50 is provided at the opposite ends of the primaries 6, 7.

During operation of the LVPT system 2 with the LVPT 1 so excited, the independent magnetic fluxes created in the core 14 by the respective sections of the respective primaries 6, 7 with which the core is aligned, i.e. turns of those sections are cut by the core, are combined in the core to produce an output flux. The phase of the output flux depends on the number of turns of the primaries cut by the core and the polarity of the connections of the primary sections cut by the core. Such output flux induces an AC output signal in the secondary 18 the phase of which will correspond directly to that of the output flux and, thus, will be indicative of the relative position of the core with respect to the primaries 6, 7. Since the secondary 18 is preferably uniformly wound the position of the core with respect to the secondary will not ordinarily affect the output signal.

During such operation of the LVPT 1, the distance between the relatively remote edges of primary sections A_4 and A_3' or B_4 and B_3' represents the stroke length L measurable by the LVPT. The additional axial length occupied by the primary sections A_1, A_2, A_3, A_4', A_5' and A_6' and corresponding B primary sections with which the core 14 may align compensate for core length. Moreover, the still further axial length along the LVPT 1 occupied by the primary sections A_{22}', A_{23}', A_{24}', A_7', A_8' and A_9' and corresponding B primary sections, with which the core 14 ordinarily will not align as constrained by conventional means, not shown, provide antifringing function to avoid non-linearities in the output signal due to flux lost at the ends of the LVPT as the core approaches the extremities of its stroke. However, all of the A and B primary 6 and 7 sections are, respectively, connected together in series as described above to provide two distinct, complete continuous primaries.

The AC output signal from the secondary is delivered via line 51 to a signal conditioning circuit 52 in the demodulator. The signal conditioning circuit may be, for example, a squaring circuit and provides a phase modulated square wave signal to a digital phase detector 53. The detector 53 compares the phase of the square wave signal from the conditioning circuit 52 with that of the reference signal on line 46 and delivers on line 54 a number of pulses from the clock oscillator 40 representative of the phase difference. That serial digital data is converted by a serial to parallel converter 55 to parallel digital information, which may be used by external equipment, fed back for controlling the external device coupled to the LVPT, etc. Such circuitry is described in more detail in the above-mentioned US Patent No. 4,134,065. The phase difference or phase quantity and the digital information derived therefrom represent the position of the core with respect to the primaries.

The degree of phase nonlinearity of the output signal with respect to displacement in inversely related to the number of times the error function of the LVPT's system theoretical phase passes through zero. In the case of the above-described example, the phase of the output signal will have zero deviation from the theoretical phase at 24 discrete positions along the stroke length L, namely when the core is effectively fully aligned with any given six adjacent sections of the primaries, such as with sections A_{13} through A_{18} of primary 6 and B_{13} through B_{18} of primary 7, as illustrated in Fig. 1. The theoretical error envelope of the output phase, then, is about ±.018%, with this error function being approximately a full order of magnitude improvement or reduction over prior LVPT's using approximately 2 to about 6 primaries and in some instances more than two excitation phases.

Furthermore, it has been discovered that the output voltage magnitude in the exemplary LVPT 1 described above will vary less than about ±1% with stroke as compared to up to about 30% deviation in the prior LVPT's such as the one disclosed in US Patent No. 4,134,065. However, as the quantizing

number M described above is increased, the error function and the voltage deviation will be reduced
further. The magnitude of the output signal, then, can be used to indicate the operative condition of the
LVPT system 2, whereby a substantial change in such magnitude from the expected level indicates a
fault.

5   **Claims**   5

1. A displacement to phase transducer, comprising plural primary means for producing in
response to alternating current excitation alternating magnetic fluxes, combining means for producing
an output flux having a phase dependent on the relative positions of said combining means and said
primary means, at least one of said combining means and primary means being movable relative to the
10   other, and output means for producing an output AC electrical signal having a substantially constant   10
magnitude and a phase corresponding to the phase of said output flux.

2. The transducer of claim 1, wherein each primary means includes plural axially displaced,
coaxial segments.

3. The transducer of claim 2, wherein segments of one primary means overlap respective
15   segments of a second primary means.   15

4. The transducer of claim 3, wherein each segment includes a plurality of electrically continuous
winding turns circumscribing the axis of the transducer.

5. The transducer of claim 4, wherein all of the segments of said one primary means are
electrically connected in series, and all of the segments of said second primary means are electrically
20   connected in series.   20

6. The transducer of claim 5, further comprising power supply means for delivering alternating
current excitation signals to said primary means to excite the same.

7. The transducer of claim 6, wherein said power supply means includes means for supplying a
first AC excitation signal to said one primary means and a second AC excitation signal that is in
25   quadrature relative to the first AC excitation signal to said second primary means.   25

8. The transducer of claim 4, wherein the number of winding turns in respective segments along
such axis of the transducer varies according to a sinusoidal function of relative position along such axis.

9. The transducer of claim 8, wherein the number of winding turns in respective segments of said
first primary means varies according to a sine function of relative position along such axis and the
30   number of winding turns in respective segments of said second primary means varies according to a   30
cosine function of relative position along such axis.

10. The transducer of claim 9, wherein in each respective primary means for those segments for
which the respective sine or cosine function is of one plurality such segments are electrically connected
in the respective primary means in a first polarity relation to produce respective electromagnetic fields
35   that are in phase, and for those segments for which the respective sine or cosine function is of the   35
opposite polarity such latter segments are electrically connected in the respective primary means in an
opposite polarity relation to produce respective electromagnetic fields that are in phase with each
other but of opposite phase polarity to such first-mentioned electromagnetic fields.

11. The transducer of claim 1, wherein the transducer has an axis, each primary means includes a
40   plurality of generally circumferential winding turns distributed along said axis according to a sinusoidal 40
function of position along said axis, and said primary means are coaxial and overlapping.

12. The transducer of claim 11, wherein said output means comprises a secondary having a
plurality of generally circumferential winding turns distributed along said axis in parallel coaxial and
coextensive relation to said primary means.

45   13. The transducer of claim 11, wherein one of said primary means is distributed along said axis   45
according to a sine function and another of said primary means is distributed along said axis according
to a cosine function.

14. The transducer of claim 13, further comprising power supply means for effecting alternating
current excitation of said primary means, respectively, in quadrature relation.

50   15. The transducer of claim 13, wherein said output means comprises a secondary having a   50
plurality of generally circumferential winding turns uniformly distributed along said axis in parallel
coaxial and coextensive relation to said primary means.

16. The transducer of claim 1, wherein said combining means comprises a magnetically
permeable core movable relative to said primary means.

55   17. The transducer of claim 2, wherein said combining means comprises a magnetically   55
permeable core movable relative to said primary means, said core having an axial length at least equal
to the axial length of the longest of said segments.

18. The transducer of claim 1, further comprising an elongate axis, wherein said primary means
each includes plural generally circumferential winding turns distributed along the axial length of said
60   axis according to a sinusoidal function of position, a hollow interior passage being circumscribed by   60
said primary means, and wherein said combining means comprises a magnetically permeable core
relatively movable in said interior along said axis.

19. The transducer of claim 18, wherein said primary means comprises two of the same
positioned in coextensive overlapping relation along said axis, and said output means comprises a

secondary having a plurality of generally circumferential winding turns uniformly distributed along said axis in coextensive relation with said primary means.

    20. The transducer of claim 19, wherein all of the winding turns of each primary means are, respectively, connected in electrical series, and in each of said primary means according to the respective sinusoidal function some of said winding turns are so connected to direct current in one direction about said axis and some of said winding turns are connected to direct current in an opposite direction about said axis.

    21. The transducer of claim 20, further comprising power supply means of exciting said primary means, respectively, with equal magnitude AC excitation signals in quadrature relation.

    22. The transducer of claim 19, wherein a portion of each primary means at each extremity of said axis comprises anti-fringing primary means for compensating for fringing effect, and said core is restrained from moving into alignment with said anti-fringing primary means.

    23. The transducer of claim 1, further comprising driving circuit means for delivering respective AC excitation signals to said primary means, and wherein said output means includes a secondary coextensive with said primary means, and in which such output AC electrical signal is induced by said combining means as an analog signal, and demodulator means for converting such analog signal to digital information representative of the relative positions of said primary means and said combining means.

    24. A displacement to phase transducer, comprising plural segmental and generally coaxial primary means for producing in response to alternating current excitation alternating magnetic fluxes, combining means for producing an output flux having a phase dependent on the relative positions of said combining means and said primary means, at least one of said combining means and primary means being movable relative to the other, and output means for producing an output AC electrical signal having a phase corresponding to the phase of said output flux.

    25. A displacement to phase transducer, comprising plural primary means for producing in response to alternating current excitation signals having a phase separation respective alternating magnetic fluxes, combining means for producing an output flux having a phase dependent on the relative positions of said combining means and said primary means, at least one of said combining means and primary means being movable relative to the other, the maximum variation of said phase of said output flux with respect to the maximum displacement of said combining means and primary means being larger than said phase separation of said excitation signals, and output means for producing an output AC electrical signal having a phase corresponding to the phase of said output flux.

    26. A displacement to phase transducer substantially as herein described with reference to the accompanying drawing.